



BARBARA COHEN is a planetary scientist at NASA's Marshall Space Flight Center.

Stories in Stone

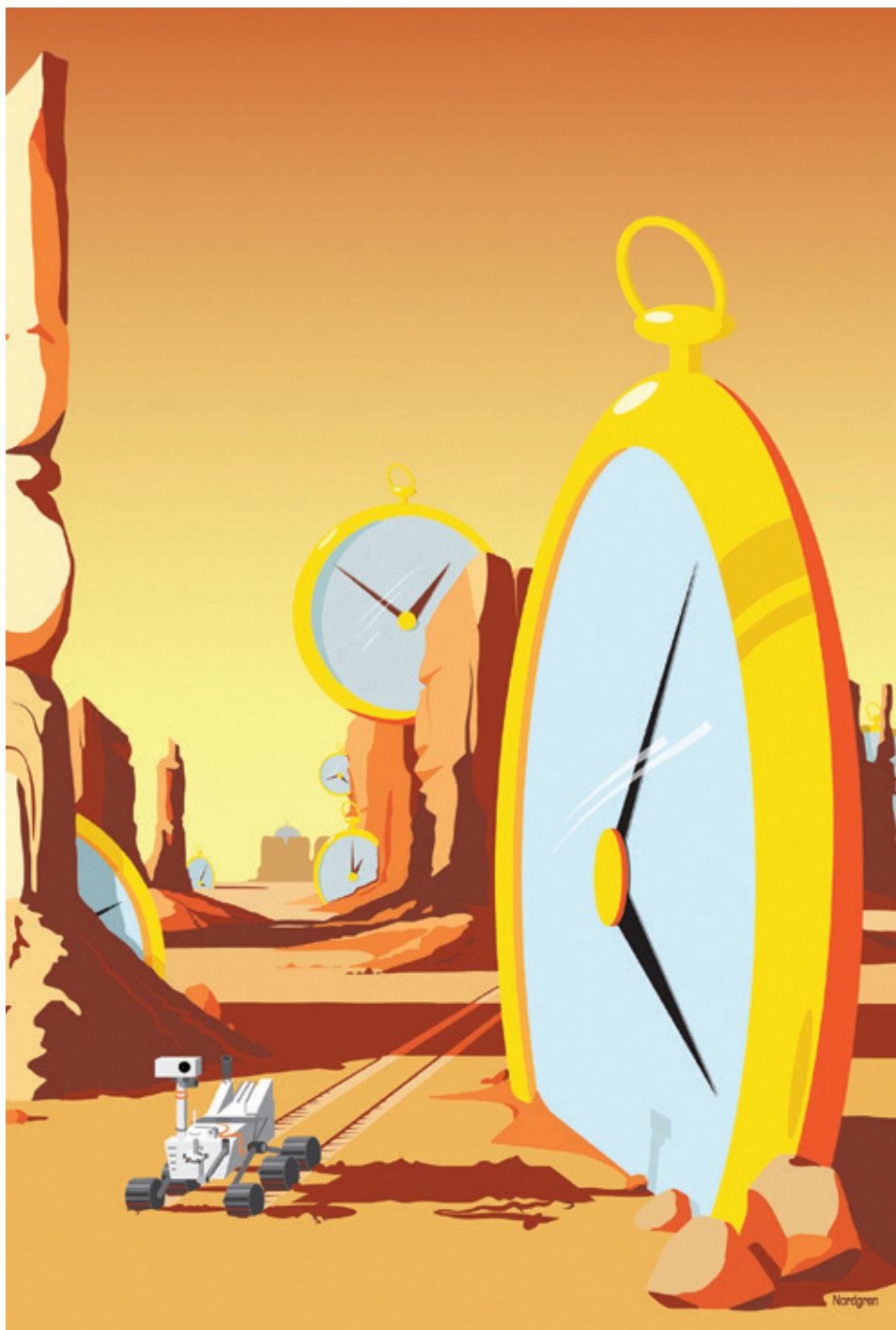
Reading a Planet's History in Its Rocks

THE STORY OF A PLANET is told through its rocks. Every rock that forms captures its environment—the grain size of a sediment tells us how far the particles were transported, the trace elements in igneous rock tell us what the magma source was, the mineralogy of a metamorphic rock tells us how much pressure it endured. A rock tells us whether an area was wet or dry, whether the fluids percolating through it were warm or cool, whether the surface was disturbed by impact breakup or tectonic folding. Every rock is a page in the book of a planet's history.

Geochronology is what puts the pages in order. It is the study of how old rocks are and when they were affected by geologic events. We know the conditions under which rocks form using instruments on our rovers, such as *Opportunity* and *Curiosity*, and on our orbiters like the *Lunar Reconnaissance Orbiter*, *MESSENGER*, and *Cassini*. Geochronology is an additional measurement that puts those conditions into a time context. That allows us to put planetary events in order and also ties them to other events in the solar system. For example, what was happening on Earth when Mars changed from a warm, wet climate to its current inhospitable state? When did impacts pummel the asteroids, Mars, and the Moon? Geochronology can also tell us how long events lasted—how long did different planets have interior heat sufficient to drive magmatic systems? How much time did organisms have to thrive in a warm, wet Martian environment? How long have surfaces been exposed to (and possibly changed by) the space environment?

SAMPLES IN THE LAB

I describe myself as a sample person. I love getting my hands on rocks from other



BELOW The image below is a thin section of Dhofar 025, one of the lunar meteorites with impact melt blebs that I've studied. It was taken using backscattered electrons in a scanning electron microscope. Here, dark and medium grays mean lighter elements that make up typical rocks and minerals, while bright white means heavier elements, such as metals, and black areas are holes or void space. The inset is a close-up of an impact-melt clast in this meteorite—a single rock bit made up of many crystals of minerals that are intergrown, having melted and recrystallized in an impact on the Moon.

planets—*Apollo* lunar samples, meteorites from around the world—opening them up, and analyzing them to find out how and when they formed. I started learning different laboratory techniques while I was an undergraduate geology major at the State University of New York at Stony Brook, one of the first places to analyze the *Apollo* samples back in the 1970s. When I attended graduate school at the University of Arizona to focus on planetary science, I developed a project using geochronology to date tiny blebs of impact melt that were preserved in lunar meteorites. The *Apollo* samples that formed in large impacts on the Moon all mysteriously have similar ages of about four billion years, which some workers have taken to mean there was an increase in bombardment of the Moon at that time—a bombardment that Earth could not have escaped. When I was doing my dissertation,

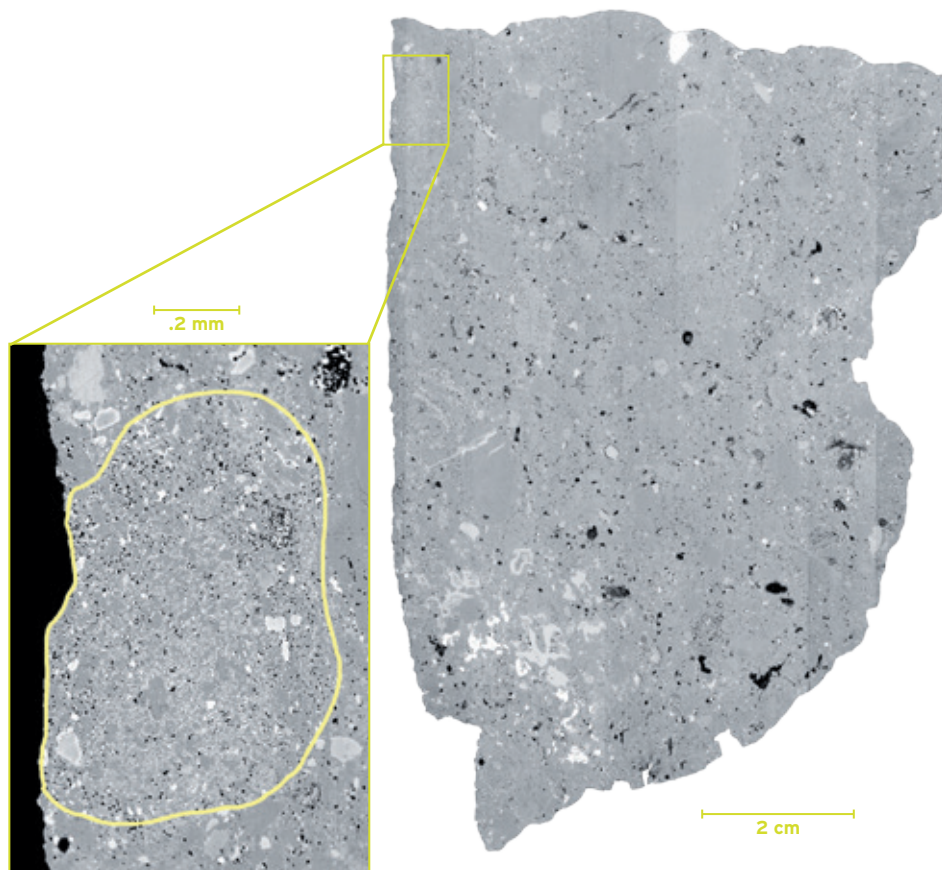
I thought for sure I would find older impact melt rocks, and I would solve this mystery. In fact, I found nothing older than four billion years in any of my samples. It's harder than I thought.

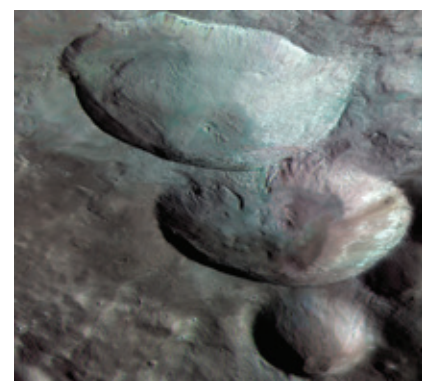
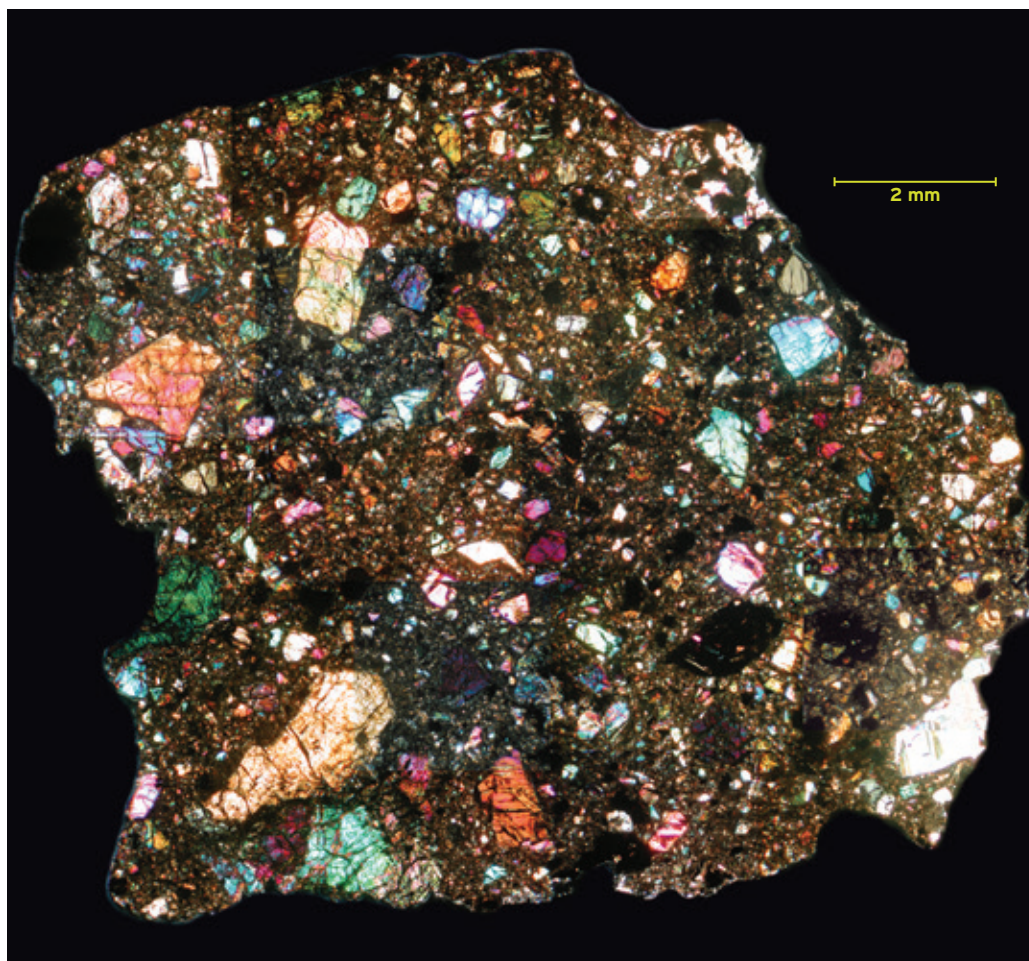
When we don't have samples to pick apart in the lab, how can we tell how old a planet is? We use relative ages. Older rock units underlie younger ones—this is the principle of stratigraphy, which you can see in places like the Grand Canyon. When we have only orbital images, it's harder to see layers stacked on top of each other, but we can use features such as lava flows and impact craters to distinguish younger areas from older ones. In fact, impact craters are quite useful because, since that time of heavy bombardment four billion years ago, they seem to form at a constant rate. This means the number of craters on a surface can be tied to its age, like leaving a piece of paper outside as it begins to rain.

But how do we tell how many craters correspond to what age? We need a tie-point, or an absolute age. On the Moon, the *Apollo* astronauts returned samples from the nearside lava flows. We dated them in the laboratory to get an age, then counted the craters on the surface of the lava flow, and created a calibrated time scale for the Moon. Now, we could count craters on parts of the Moon where we didn't visit, and use their relationship determined using the *Apollo* samples to infer the surface age. Even further, we can use this calibration to extend crater counts on other planets like Mars to estimate planetary surface ages, although it has a lot of uncertainties when used this way.

IN SITU SAMPLING

In 2004, I was part of a committee that advised NASA on what lunar science will be important to do when humans return to the Moon. "The Scientific Context for Exploration of the Moon" was our report, and the committee agreed that the early bombardment of the Moon, the time period when





ABOVE This row of impact craters, imaged by Dawn, is one of the most striking features on the large asteroid Vesta. These and other impacts on Vesta have churned up its surface, creating a regolith.

LEFT This magnified thin section (QUE 94200) is a howardite, which is a sample of Vesta's regolith. It's from a group of meteorites linked to Vesta, called HEDs (howardite, eucrite, diogenite). This sample contains small pieces of impact-melted material from Vesta's craters. However, since we don't know exactly where on the asteroid these meteorites originated, we can't yet link the absolute ages of samples to crater counting on its surface.

the huge nearside basins like Imbrium and Orientale were formed, was a huge outstanding question with important implications for the entire solar system. We advocated for more samples—samples from different places on the Moon, not just the nearside Apollo sites. In fact, we need samples from many places. For example, Mars sample return is a longstanding goal of the planetary science community. Our meteorites tell us when their parent bodies formed and evolved, but where are their parent bodies? A lot of asteroids need sample return, too. And the smooth, lightly cratered surface of Venus, the iron-poor crust of Mercury—when did they form?

Get sample returns from all these places? Clearly, that's not practical. But I learned of

another approach to sampling when my lunar science colleague and fellow Committee member Paul Lucey asked me about in situ geochronology, which basically means taking our lab out into space instead of bringing the samples back. I pshawed at the idea. I told him how we need clean room sample preparation and handling, eking out sensitivity from instruments that took up half a room, to obtain ages precise within millions of years on tiny specks of billion-years-old samples.

Paul shook his head disappointedly at me and said, “Really? You can’t think of a single question in all of planetary science that could be addressed with a slightly less precise age?” I stopped in my mental tracks. Well, we don’t know the age of the Martian highlands within about a half billion years.

BELOW Most scientists agree that ALH84001 is the oldest Mars meteorite ever found. This piece of the Red Planet crystallized 4.51 billion years ago. Half a billion years later, while residing on the Martian surface, it was affected by an impact shock event. We don't know where on Mars this meteorite originated, so we can't tie its age to a Martian crater count.



That's a wide range. If we could narrow that transition to even within 100 million years, it would be enough to tie it to lunar history. Young lunar basalts; key craters on the Moon, Mars, Vesta; magmatic age of differentiated asteroids—all these could be addressed to a first cut with an idea like this.

TIME AND DECAY

Our methods of absolute dating rely on radiometric decay. Each element in the periodic table has a set number of protons and electrons, which give the element an identity. For example, carbon has six protons and six electrons. All atoms also have neutrons in their nucleus, and these can vary in number. Atoms that have the same number of protons but different numbers of neutrons are called isotopes of each other. So, a carbon atom with six neutrons is ^{12}C and one with seven neutrons is ^{13}C . Many elements have naturally radioactive isotopes, where the parent atoms decay over time to more stable daughter atoms. Radioac-

I use a radioactive system based on potassium (K) decaying to argon (Ar). Potassium is a naturally occurring element in our everyday life, found in bananas and granite countertops, but a very small number of potassium atoms have extra neutrons and are radioactive. When potassium is in a mineral or rock, it forms part of a lattice. When it decays to argon, a noble gas, the argon is trapped inside the lattice. So, we can take a rock and measure its parent potassium and its daughter argon, and know how long argon has been building up—or the age of the rock. With a half-life of 1.29 billion years, the potassium-argon system is a nice one for solar system rocks and has been used on Moon rocks and meteorites, as well as terrestrial rocks.

THE POTASSIUM-ARGON LASER EXPERIMENT

It was my former graduate advisor Tim Swindle who first tried to develop the potassium-argon system for use in a flight



ABOVE Scientists use stratigraphy to learn the relative age of rocks. Like the different colored strata in the Grand Canyon show, younger rocks overlie older rocks. To know their absolute age, the rocks need to be analyzed in a laboratory.

tive elements decay at a known rate, so if we can measure the parent and the daughter, we know how long the system has been decaying; or for rocks, the time the rock formed.

instrument. Tim called his approach the Argon Geochronology Experiment (AGE), and he meant to fly it on a Mars mission. AGE used a laser (like Chemcam on *Curios-*

BARBARA COHEN Barbara Cohen is interested in the geochronology and geochemistry of planetary samples from the Moon, Mars, and asteroids. She is a principal investigator on multiple NASA research projects, a member of the Mars Exploration Rover mission team still operating Opportunity, and the principal investigator for Lunar Flashlight, a lunar CubeSat mission that will be launched in 2018 as a Space Launch System secondary payload. Asteroid 6186 Barbcohen is named for her.

ity) to measure potassium in small samples, then melted it in a 1,500-degree Celsius (2,730 Fahrenheit) oven to liberate the trapped argon.

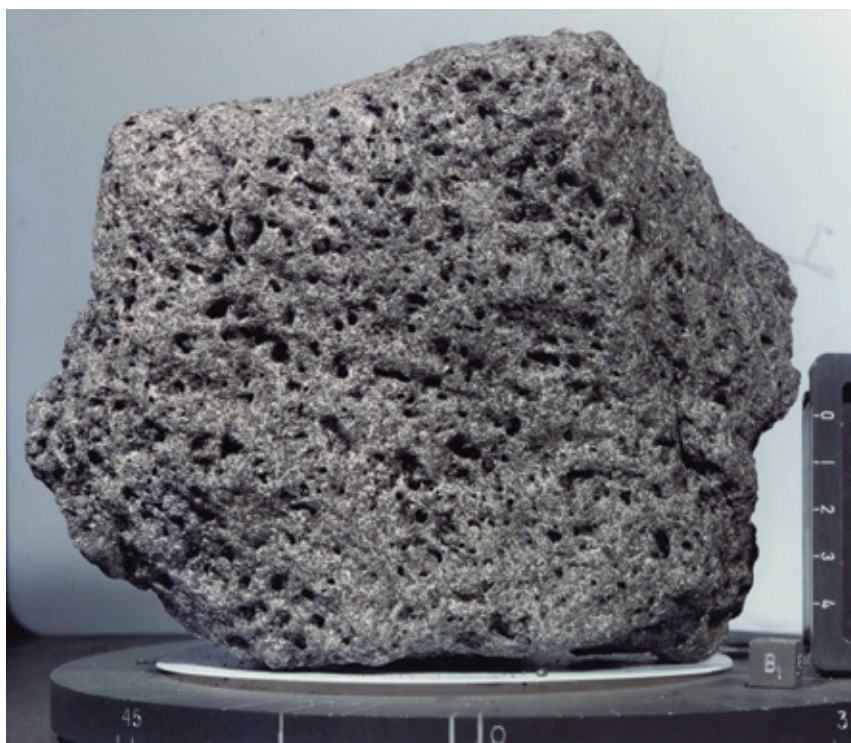
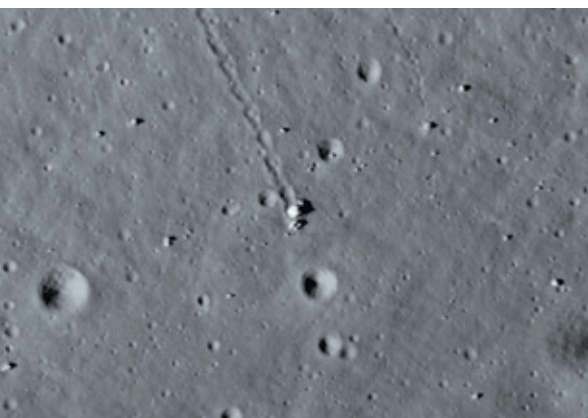
I was a collaborator on Tim's proposals. In a conversation with him at a meeting at NASA Ames in 2008, I mused that the high-energy laser would break up the crystal lattice and set the argon free without needing an oven. I asked Tim if he'd like to try this approach but, explaining that he was coming to the end of his development grant and taking on other responsibilities, he suggested that I try it myself. We switched roles, and I began developing the Potassium-Argon Laser Experiment (KArLE) with Tim as my collaborator.

Since I'm a scientist, not a technologist, I designed KArLE with the principle of taking instruments that already exist for planetary surface missions and using them to make a new measurement: the rocks' age. KArLE uses a Chemcam-like instrument to

giving accurate ages with about 10 percent to 15 percent uncertainties. This level of precision is great for answering lots of planetary science questions.

We can make the potassium and argon measurements well, but an age is the interpretation of a geologic event, so each KArLE component helps make context measurements to interpret the sample's age. For example, the surface textures of a rock are characterized with the imager, LIBS provides a complete elemental analysis of the rock, and all the liberated gases can be measured. I thought I was being

BELOW LEFT *Mare Serenitatis is one of the lunar maria, vast lava plains on the Moon's surface. This is a Lunar Reconnaissance Orbiter Camera (LROC) view of Station 6, where Apollo 17 astronauts explored a collection of boulders and regolith. Five large boulder fragments lie at the base of a long boulder trail. All are from a single boulder that rolled down the hill and broke apart.*



both ablate a rock sample and measure the K in the plasma state using laser-induced breakdown spectroscopy (LIBS). As the rock breaks down, we measure the liberated Ar using mass spectrometry, like the kinds that are used in such missions as *Curiosity*, *LADEE*, and *Cassini*. We've had about three years to develop a KArLE laboratory breadboard and test it on planetary analog samples with encouraging results,

quite clever by repurposing these components and using them for geochronology. But a good idea is sometimes just waiting to be had and, quite independently, two other groups in Japan and France were developing this technique nearly simultaneously with us. Fortunately, over the last several years, we have come to think of each other as collaborators working toward a common goal.

ABOVE RIGHT *Pieces of the Mare Serenitatis lava flow were returned to Earth and dated in laboratories, where an absolute age for the flow's formation was found to be between 3.7 and 3.8 billion years. This is a piece of the Apollo 17 basalt that yielded this age, linking crater counting from the image at left.*



KATE HOWELLS is The Planetary Society's Volunteer Network Manager.



ABOVE Barbara is holding a shatter cone (a piece of a terrestrial impact crater) in her laboratory at NASA's Marshall Space Flight Center.

OPPORTUNITIES FOR IN SITU DATING

The capability of flight instruments to conduct in situ geochronology is called out in the NASA Planetary Science Decadal Survey and the NASA Technology Roadmap as needing development to serve the community's needs. *Beagle 2*, the exobiological lander for ESA's *Mars Express* orbiter, is the only Mars mission launched to date with the explicit aim to perform in situ K-Ar isotopic dating of rocks. Unfortunately, the *Beagle 2* lander failed to communicate during its first expected radio contact, and this science objective was not fulfilled. The first in situ K-Ar date on Mars was recently published, using SAM and APXS measurements on the Cumberland mudstone. The age of 4.21, plus or minus 0.35, billion years ago for Cumberland suggests that it records a very old formation age and validates the idea of potassium-argon dating on other planets, though the Curiosity method is very imprecise. To get more precise and meaningful ages, several groups are developing dedicated in situ dating instruments. The latest opportunity for an in situ dating instrument came last year when the Mars 2020 payload was being competed. Four in situ dating instruments using potassium-argon and other radioactive dating schemes were proposed, including KArLE. Though none won a place on the Mars 2020 rover, in situ dating may soon become a reality.

There are lots of questions in planetary science that still will require the precision of laboratory measurements and need samples back on Earth to address. In situ dating doesn't replace sample return, but rather extends our ability to use it as a tool, along with our imaging and compositional tools. I want it to be a common tool that we can use on the Moon, Mars, asteroids, and beyond. Wouldn't it be romantic to have a date in all those places? 🌌

To read an in-depth paper on KArLE and geochronology by Barbara Cohen and team, go to planet.ly/karle.

Volunteers!

THE PLANETARY SOCIETY'S volunteers around the world have been doing some great community outreach over the past few months. Here is a stellar example:

Members of a student group called the Space Exploration Society-Berkeley (SESB), represent The Planetary Society at the University of California at Berkeley. The club organizes activities and events aimed at promoting space science and exploration in the student community, in collaboration with both The Planetary Society and Students for the Exploration and Development of Space.

Among other things, SESB students organize star parties, field trips, movie nights, and lectures by local professors. This year the club also started hosting a series of space forums—student-facilitated talks on topics related to space exploration. Topics so far have included “The Past, Present, and Future of Space Propulsion;” “Mars Exploration;” “SETI: The Search for Extra Terrestrial Intelligence;” and “Man Versus Machine: The Future of Space Exploration.” SESB students are also developing their own research projects, including a weather balloon to be launched as part of Berkeley's campus-wide Science, Technology, Engineering, and Math (STEM) Day.

The Planetary Society is proud to have members and volunteers around the world who are this committed to the future of space exploration. Check out planetary.org/volunteer to read more stories about our volunteers at work, and to find out how to get involved. 🌌



Photo: Courtesy of the author